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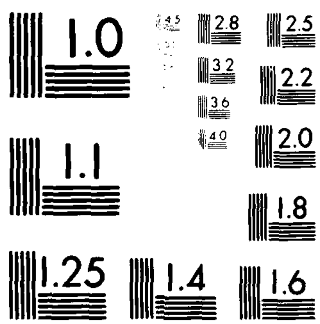

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Evaluating soil moisture and textural relationships using regression analysis

Melvin B. Satterwhite

MAY 1980

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U.S. ARMY CORPS OF ENGINEERS
ENGINEER TOPOGRAPHIC LABORATORIES
FORT BELVOIR, VIRGINIA 22060

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Soil moisture and textural conditions are described for 179 soil samples from an arid to semiarid climate. Stepwise multiple regression analysis of these data produced four regression equations that related (1) the percent sand and clay and (2) the percent fines, with the percent soil water held at 0.33 bar (FC) and the 15 bar (WP) potentials. Evaluation of these equations showed no differences between the estimates at the 0.33 bar potential using either the percent sand and clay or the percent fines. Better estimates for the WP were obtained when the percent sand and clay were used instead of the percent fines. The

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differences between the estimated soil moisture at FC or WP varied less than 30 percent from the measured soil moisture values for 161 (90 percent) of the 179 soil samples. The differences between the estimated and the measured soil moisture values were not significant at the 95 percent level of confidence.

The regression equations provide a method by which the potential percent soil water held at the FC or WP can be estimated from soil textural data. The accuracy and precision of the results of applying these equations to soils of other areas has not been determined. It would seem, however, that they would be applicable in those instances where only general working estimates are needed.

SUMMARY

Soil moisture and textural conditions can affect trafficability and cross-country movement; hence, a need exists to improve the capability of estimating soil water conditions. Because soil moisture characteristics are highly correlated with the soil textural conditions, it should be possible to predict certain soil moisture parameters from a knowledge of the soil texture conditions.

The purpose of this study was to develop and evaluate regression equations for estimating the soil field capacity (FC) (0.33 bar potential) and the wilting point (WP) (15 bar potential) from soil textural data. The percent soil water retained at FC and WP were determined in the laboratory for 179 soil samples. A stepwise multiple regression analysis of the soil textural and soil moisture data was made, which resulted in four regression equations from which the percent soil water at the FC and WP could be predicted from knowing (1) the percent sand and percent clay, and (2) the percent fines (silt and clay) in the soil. The differences between the estimated and the measured soil moisture values were not statistically significant at the 95 percent confidence level. Estimates of the FC, based on the percent sand and clay, were essentially the same as those made using the percent fines. For the WP, better estimates of the percent water were obtained by using the percent sand and clay rather than the percent fines; however, neither estimate was significantly different from the measured soil moisture levels. Absolute percent error for the estimates was less than 30 percent for 90 percent of the soil samples, 161 of 179 samples.

An evaluation of reported regression equations, which were developed for another arid area, was made by using soil data from this study. Although these equations were very similar to the ones developed in this study, the soil water estimates varied significantly from the measured values. Even so these equations were useful in that they provided acceptable working estimates.

PREFACE

This study was conducted under DA Project 4A161102B52C, Task C, Work Unit 0010, "Indicators of Terrain Conditions." The study was done during the period January 1979 to June 1979 under the supervision of Dr. J. N. Rinker, Team Leader, Center for Remote Sensing; and Mr. M. Crowell, Jr., Director, Research Institute.

COL Daniel L. Lycan, CE was Commander and Director and Mr. Robert P. Macchia was Technical Director of the Engineer Topographic Laboratories during the study period.

Conversion factors for soil moisture tension are given by the following relationships:

$$1 \text{ bar} = 1.00000 \times 10^5 \text{ pascals}$$

$$(\text{atmosphere standard}) = 1.01325 \times 10^5 \text{ pascals}$$

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INTRODUCTION

Most studies of soil moisture texture relationships have been applied to crop production. However, the studies can be applied to trafficability and cross-country movement, particularly where estimates of soil-water characteristics and soil conditions are needed. Previous works, using different textured soils, have shown that the soil water retained at the 0.33 and 15 bar potentials (field capacity and wilt point, respectively) was inversely proportional to the percentage of coarse sand and directly proportional to the percentages of clay, silt, or organic carbon.[1,2] From these relations, regression equations were developed from which estimates of the water capacity of the soil can be made from mechanical analysis soil data.

According to some authors, there are limitations on the application of the regression equations. Salter and Williams[3] reported that their regression equations could not be used for predicting soil moisture for the sandy and loamy sand soils of the U.S. Soil Classification System.[4] However, Schmugge, et al.[5] reported regression equations that could be used for predicting the soil water retention, but the estimate could vary as much as 20 percent of the actual measured values.

[1]P. J. Salter and J. B. Williams, "The Influence of Texture On The Moisture Characteristics Of Soil," *J. Soil Sci,* Vol. 20, 1969, pp. 126–131.

[2]T. Schmugge, T. Wilheit, W. Wester, and J. Gloersen, *Remote Sensing of Soil Moisture With Microwave Radiometers–II.* NASA TN D8321, N76–32625, 1976.

[3]P. J. Salter and J. B. Williams, "The Influence of Texture on the Moisture Characteristics of Soil," *J. Soil Sci,* Vol. 20, 1969, pp. 126–131.

[4]Soil Survey Staff, *Soil Survey Manual,* USDA Handbook No. 18, Washington, D.C., 1951.

[5]T. Schmugge, T. Wilheit, W. Wester, and J. Gloersen, *Remote Sensing of Soil Moisture With Microwave Radiometers--II.* NASA TN D8321, N76-32625, 1976.

One method of characterizing the water in the soil is by the strength of the binding forces between the soil particles and the water. The binding forces at high potentials are determined by the soil particles. The binding forces at intermediate potentials are determined largely by the radius of curvature of the water film between the soil particles. The binding forces. are at very low potentials, or near zero, when the soil is at, or very near, saturation. Soil water content corresponding to the 0.33 and 15 bar potentials is frequently taken as the upper and lower limits of plant-available water of the soil.[6] The 0.33 bar potential, or field capacity, is defined as the forces holding water against gravitational forces after a saturated soil has drained for several days.

For many studies, the water retained in the soil against the 0.33 bar potentials has been accepted as the approximate field capacity, or the upper limit of plant-available water; however, the actual field capacity can be closer to the water held at the 0.05 to 0.1 bar potential. Because the water content at potentials between 0.05 and 0.33 bars is generally quite large, using the 0.33 bar potential for estimating field capacity can cause underestimates of the available water capacity of a soil. However, some of this variation can be ignored because of the influence of soil structure on soil-moisture-holding characteristics.[7] Comparing water contents for disturbed and undisturbed soil samples shows that more water is held by the undisturbed sample, particularly at the lower potentials. This effect is not as great at the wilt point because water content for disturbed and undisturbed samples were almost the same.[8] The permanent wilting point has been recognized as the lower limit of plant-available water in the soils. It has been defined as that point at which the leaves of a standard plant (usually sunflower) growing in a soil reaches a wilted stage from which the plant will not recover when placed into a saturated atmosphere, without adding any more water.

[6] Daniel Hillel, *Soil and Water, Physical Properties and Processes*, Acedemic Press, New York, 1971.

[7] P. J. Salter and J. B. Williams, "The Influence of Texture on the Moisture Characteristics of Soil," *J. Soil Sci*, Vol. 20, 1969, pp. 126–131.

[8] Ibid. pp. 126-131.

The pressure membrane apparatus has been widely used as an indirect method to approximate the soil water retention at the permanent wilting point without the time-consuming efforts associated with the growth and stress of a standard plant in the soils under consideration. The soil water retained at the 15 bar potential has been widely accepted as the approximate soil water condition at which plants become permanently wilted, recognizing that some plants can extract soil water held at higher potentials. Several generalized soil moisture release curves are shown in figure 1. For most regions soil texture information is often more readily available than is soil moisture information. Therefore, to improve the capability for predicting a soil's water-holding characteristics, particularly that retained at field capacity and wilting point, one should address the relationships between soil water and soil texture data for a variety of soil conditions and climates.

The objective of this study was to develop and evaluate regression equations for estimating the percentage of soil water at the field capacity and at the wilting point by using soil texture data.

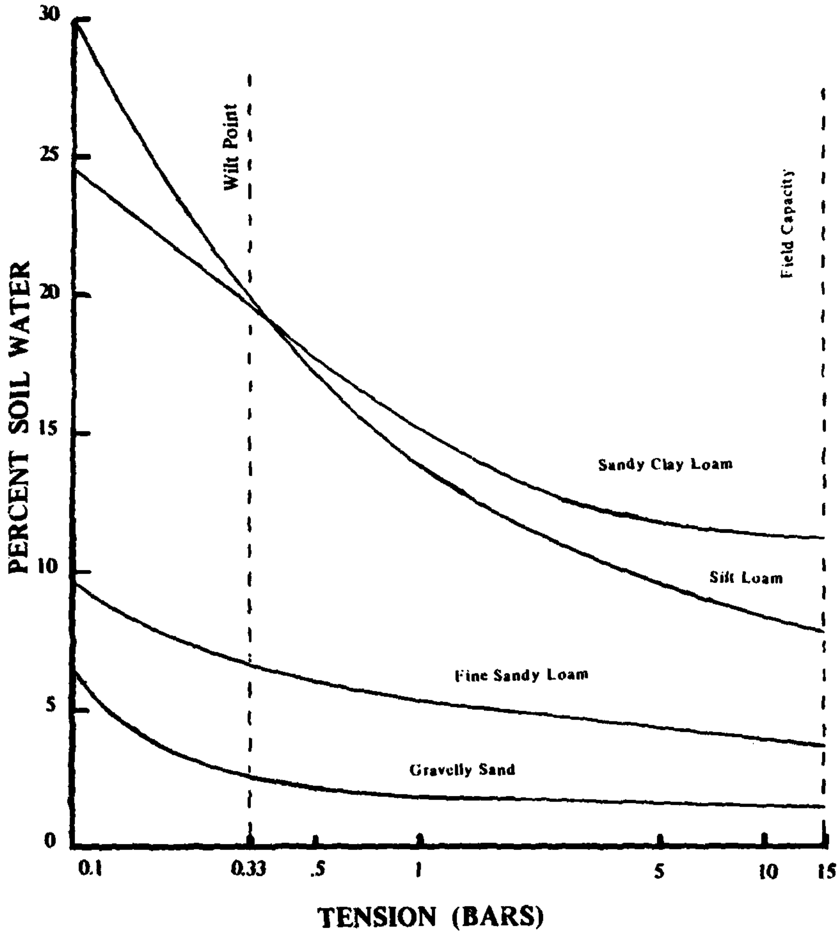

Figure 1. Soil Moisture Release Curves.

METHODS AND MATERIALS

The soil samples used in this study were obtained from the Fort Bliss Reservation in south-central New Mexico and western Texas. This area has a semiarid to arid climate (figure 2). It also has diverse landform features consisting of bolsons, playas, mesas, hills, alluvial fans, and washes, on which a wide range of soil texture conditions are present. The soils, which are on the limestone, sandstone, shale or igneous bedrock or on unconsolidated materials derived from these bedrock types, are primarily aridisols and entisols.

The soil samples were collected from all landform units and from a number of different parent materials with the samples varying widely in their texture and water retention characteristics.

Soil sample pits were dug at 128 sample sites. The depth of each soil pit was approximately 60 centimeters (24 in.) except where caliche pan (petrocalcic horizon) or bedrock were encountered. Of the 179 samples taken, 128 were taken from the 0 to 15 centimeters deep horizon (0-6 in.) and the remaining 51 were taken from 15 to 45 centimeters depth. The samples were placed into plastic bags, which were sealed, labeled, and transported to the laboratory for analysis. After air drying, each soil sample was passed through a #10 sieve (openings of 2.0mm) and the percent of the total sample retained on the sieve was determined. The sand, silt, and clay percentages were determined by using the hydrometer technique for that portion of the sample that passed through the 2.0 mm sieve.[9]

The textural names are in accordance with accepted nomenclature.[10] The standard soil textural triangle, showing the soil texture classes, is presented in figure 3.

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[9] P. R. Day, "Particle fractionation and particle size analysis," *In*: C. A. Black, "Methoas of Soil Analysis, Part 1, Physical and Mineralogolical Properties, Including Statistics of Measurement and Sampling," *Amer Soc of Agron*, Madison, WI, Agron Monog, Vol. 9, 1965, pp. 545–547.

[10] Soil Survey Staff, *Soil Survey Manual*, USDA Handbook No. 18, Washington, D. C., 1951.

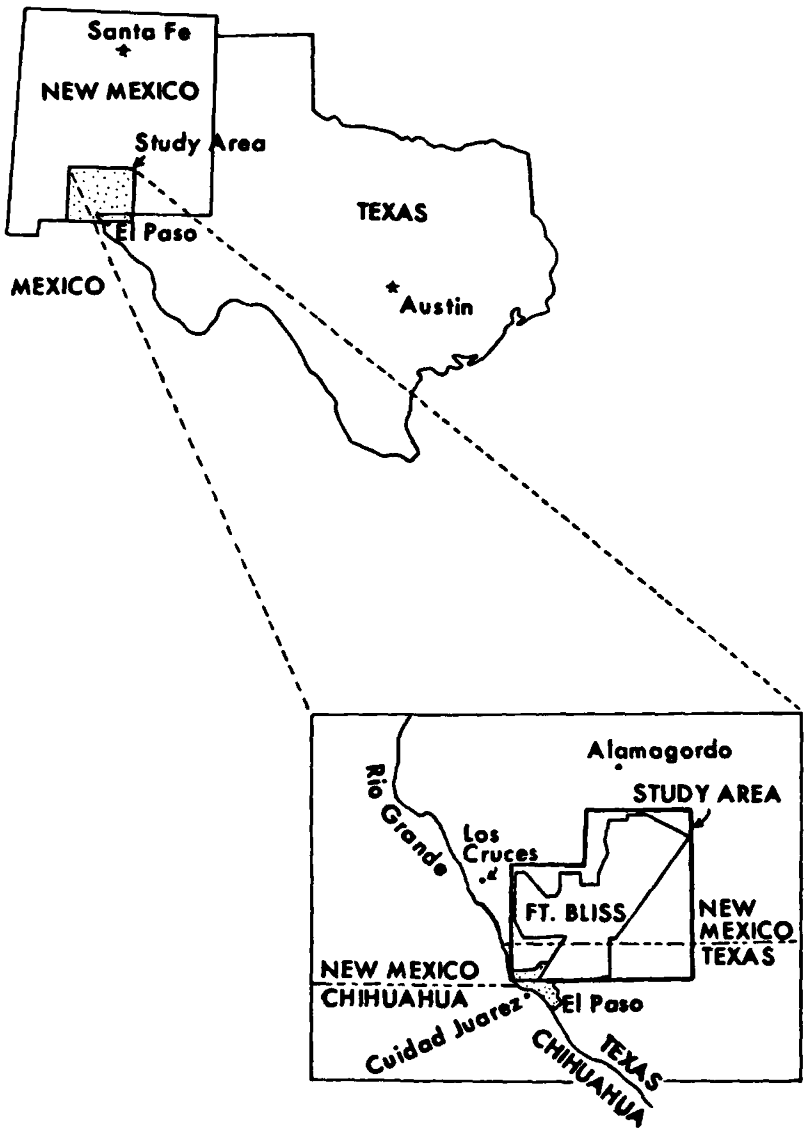


Figure 2. Map of the Study Area.

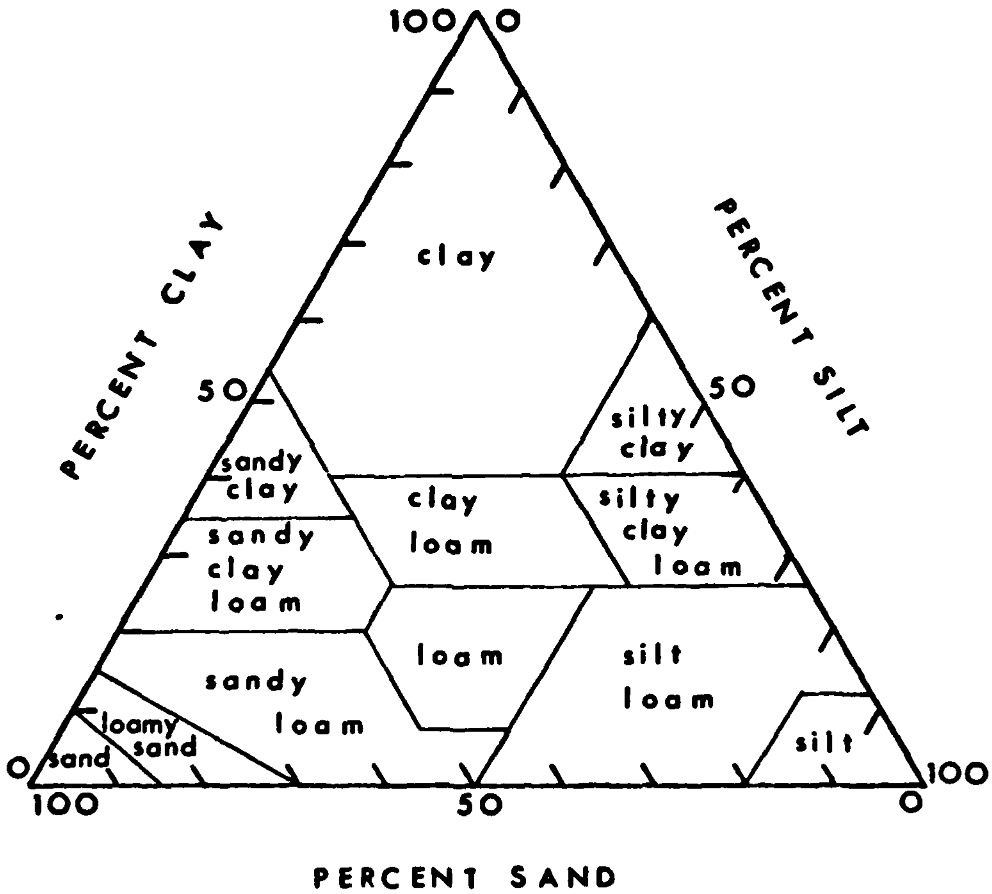


Figure 3. Soil Textural Classes Within the USDA Classification System.

An air-dried subsample of each sieved sample was analyzed for pH, salinity, and soil water retention at the 0.33 and 15 bar potentials. Soil pH was determined for 1:1 ratio of soil to distilled water by using a Beckman Instruments Model N pH meter, which had been calibrated with buffer solutions of pH 7 and pH 10. Soil salinity was determined by measuring the electrical conductivity of a 1:2 ratio of soil to distilled water using a Lab-Line Lectro MHO–METER Model Mc-1, Mark IV. Calibration of the conductivity meter was made using a 0.010 N KCl solution. Salinity in parts per million (ppm) was calculated from equation 1:

$$\text{Salinity (ppm)} = (\text{E.C.}) \times 0.64 \qquad (1)$$

where E.C. is the electrical conductivity in millimhos/cm at 25°C, and 0.64 is a conversion constant.[11]

The soil water retained by each of 179 soil samples at the 0.33 and 15 bar potentials, field capacity (FC) and wilt point (WP), was determined by using the pressure membrane technique,[12] with the 5 and 15 bar pressure extractors (Soil Moisture Equipment). Soil samples removed from the pressure extractor were oven-dried at 105°C for 24 hours. The percent soil water retained at either potential was determined gravimetrically as a percentage of the sample's oven-dry weight. The soil water percentage for the field capacity or the wilt point was determined for duplicate samples. The soil water percentages for the duplicate samples were averaged if the moisture contents for the two samples varied less than 1.0 percent. If the moisture contents varied more than 1.0 percent, additional subsamples were analyzed until an average value was calculated.

[11] L. A. Richards, (ed.), *Diagnosis and Improvement of Saline and Alkali Soils*, USDA Agricultural Handbook 60, Washington, D.C., 1954.

[12] "Operating instructions for the pressure plate extractor," Soil Moisture Equipment Corp., Santa Barbara, CA 93105.

The 1.0 percent criterion for the variation between the percent soil water of duplicate samples was within the measurement criteria suggested by Richards.[13]

Stepwise linear regression analysis was performed on the soil textural and soil moisture data to describe the relationships between the percent soil water retained at the 0.33 bar potential or the 15 bar potential with (1) the percent sand, (2) the percent clay, (3) the percent sand plus the percent clay, and (4) the percent fines (percent silt plus percent clay). The derived regression equations were then used to estimate the soil water at the 0.33 and the 15 bar potential for each sample. The measured and estimated soil water values were then evaluated using the Chi-square statistic and linear regression analysis.[14,15]

[13] L. A. Richards, "Physical condition of water in soil," *In*: C. A. Black, "Methods of Soil Analysis, Part 1, Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling," *Amer Soc of Agron*, Madison, WI, Agron Monog Vol. 9, 1965, pp 128–152.

[14] John E. Freud, *Modern Elementary Statistics*, (4th Ed.), Prentice–Hall, Inc., Englewood Cliffs, NJ, 1973, p. 532.

[15] W. J. Dixon, *Biomedical Computer Programs, Automatic Compilation No. 2.* University of California Press, Berkeley, CA, 1971, pp. 233–257.

RESULTS AND DISCUSSION

The soils collected in this study were highly variable in texture, which was anticipated because the samples were obtained from rather diverse landform features. The percent gravel ranged from 0 to 38 percent; the percent sand, from 0 to 90 percent; the percent silt, from 0 to 48 percent; and the percent clay, from 0 to 85 percent. The various soil separates and their size classifications conformed to the U.S. classification system: gravel, 76.0 to 2.0 mm; sand, 2.0 to 0.05 mm; silt, 0.05 to 0.002 mm; and clay, <0.002 mm. The soil textures were either gravelly clay, clay loam, sandy clay loam, loamy sand, gravelly loam, gravelly silt loam, silty clay, or sandy loam.

The texture data showed an inverse relationship between the sand and clay percentages in the samples. Samples with a high sand percentage had low clay content, and samples with a low sand percentage had a high clay content (figure 4).

The pH for the samples ranged from 7.4 to 8.7 and had no apparent association with the soil texture, i.e. sandy, loamy, or clayey textured soils all had pH values within this range.

Soil salinities ranged from 17 to 340 ppm total soluble salts, and were related somewhat to soil texture. Soils containing more than 70 percent sand had the lowest salinities, ranging from 17 to 180 ppm. Loamy soils ranged from 46 to 224 ppm. Soils containing more than 30 percent clay had the highest salinities, ranging from 85 to 340 ppm.

The soil water retained by the 179 soil samples ranged from 2 to 37 percent for the 0.33 bar potential, and from 1 to 23 percent for the 15 bar potential (table 1).

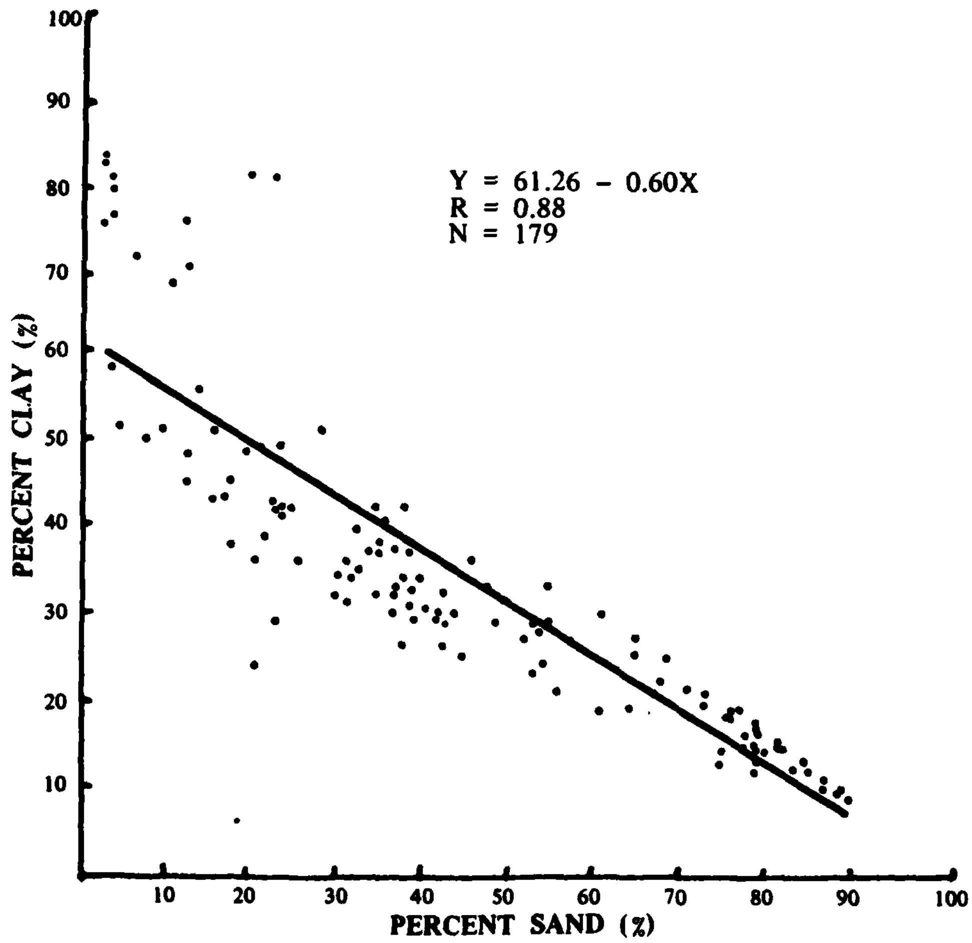


Figure 4. Distribution of Soil Samples by Percent Sand and Percent Clay.

TABLE 1. Summary of Measured and Estimated Percent Soil Water at FC and WP for 179 Soil Samples*

Soil Moisture Constant	Range (%)	Mean	SD	Chi-square
Measured				
FC	2.0-37.0	15.7	7.7	NA
WP	1.0-23.0	8.7	4.5	NA
Estimate (Sand and Clay)				
FC(a)	2.8-29.7	15.8	7.4	50.1
WP(a)	1.2-19.1	8.6	4.3	52.3
Estimate (Fines)				
FC(b)	2.6-29.6	15.5	7.3	41.3
WP(b)	1.4-16.7	8.7	4.1	55.2

SD = Standard Deviation
NA = Not Applicable

*Chi-square values were determined between estimated and measured percent soil moisture. Variation was significant at the 95 percent confidence level where Chi-square =118 for 178 degrees of freedom.

(a) FC = 32.9 – (0.33 x % sand) – (0.05 x % clay)
WP = 11.2 – (0.12 x % sand) + (0.09 x % clay)

(b) FC = –0.42 + (0.30 x % fines)
WP = –0.32 + (0.17 x % fines)

The amount of water retained in the soil was related to the soil texture. Soils holding the least amount of water at either the 0.33 or 15 bar potentials were those with a high percentage of sand. The soils holding the largest amount of water had a high percentage of clays or fines. The relationships for the sand, clay, and fines in the water retained at the 0.33 and 15 bar potentials are shown in figures 5, 6, and 7, respectively. The regression

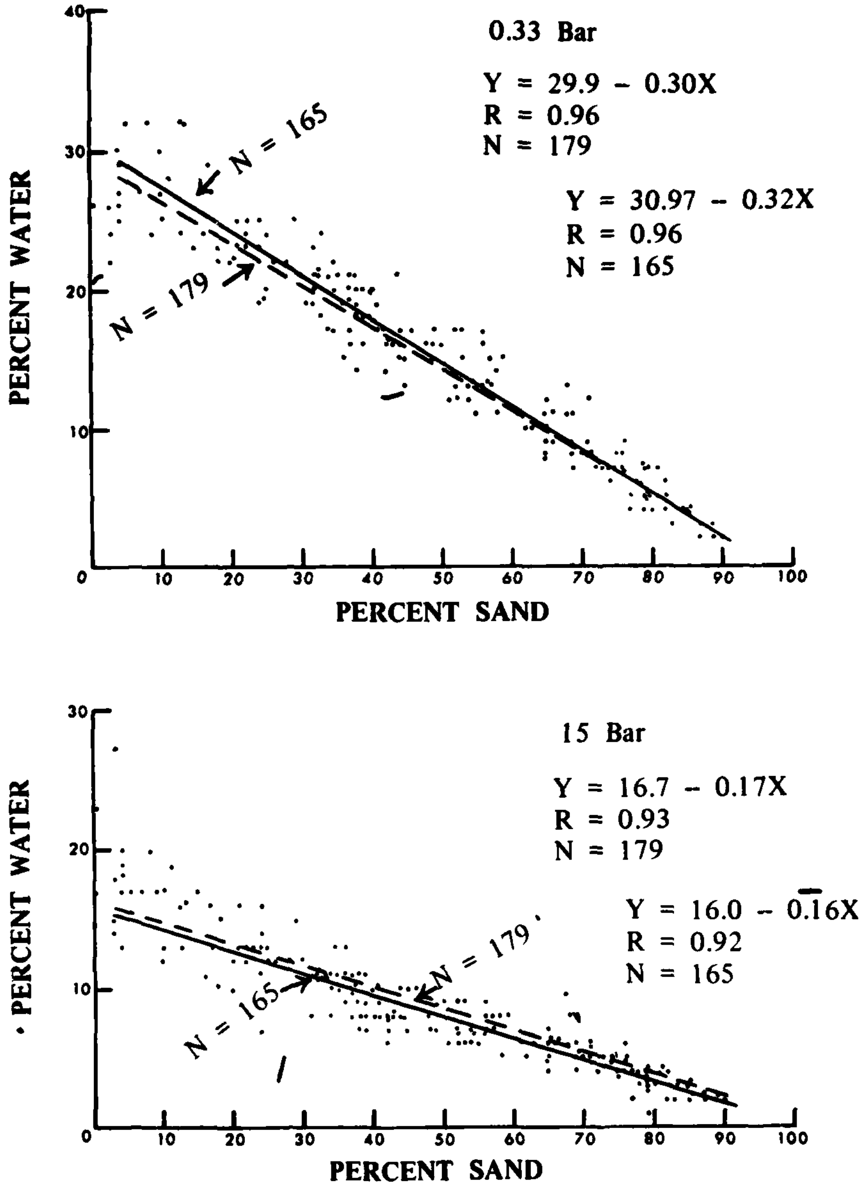


Figure 5. Percent Soil Water Held at 0.33 and 15 Bar Potential Plotted as a Function of Percent Sand.

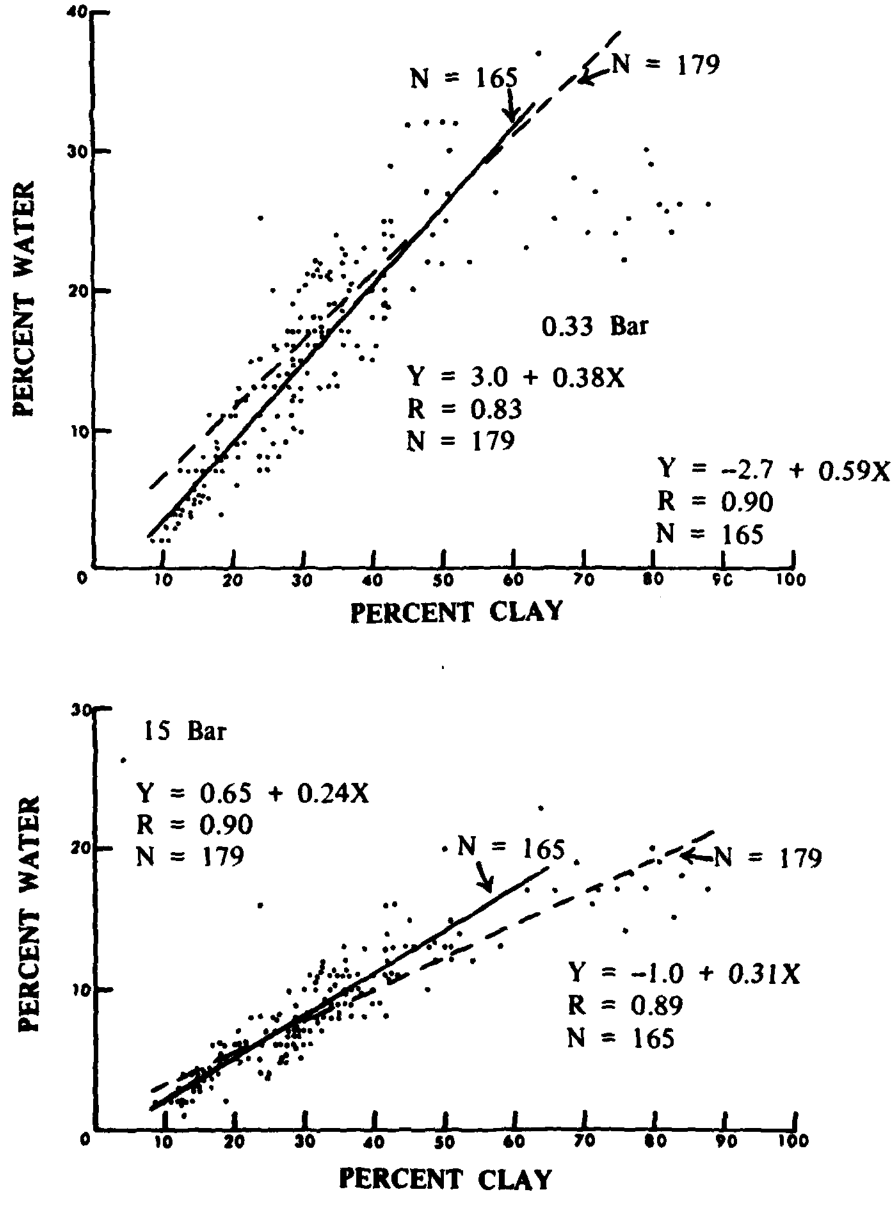
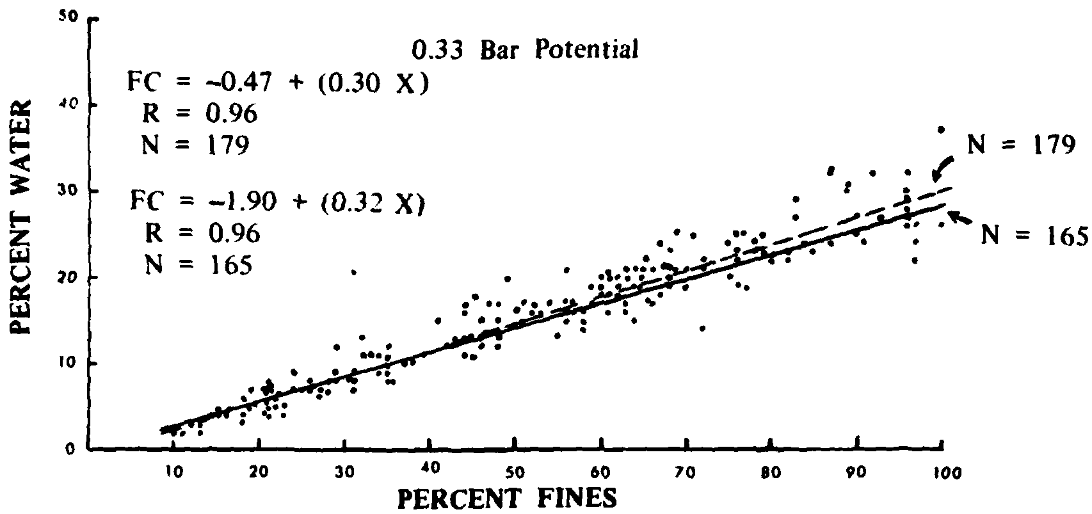


Figure 6. Percent Soil Water Held at 0.33 and 15 Bar Potential Plotted as a Function of Percent Clay.



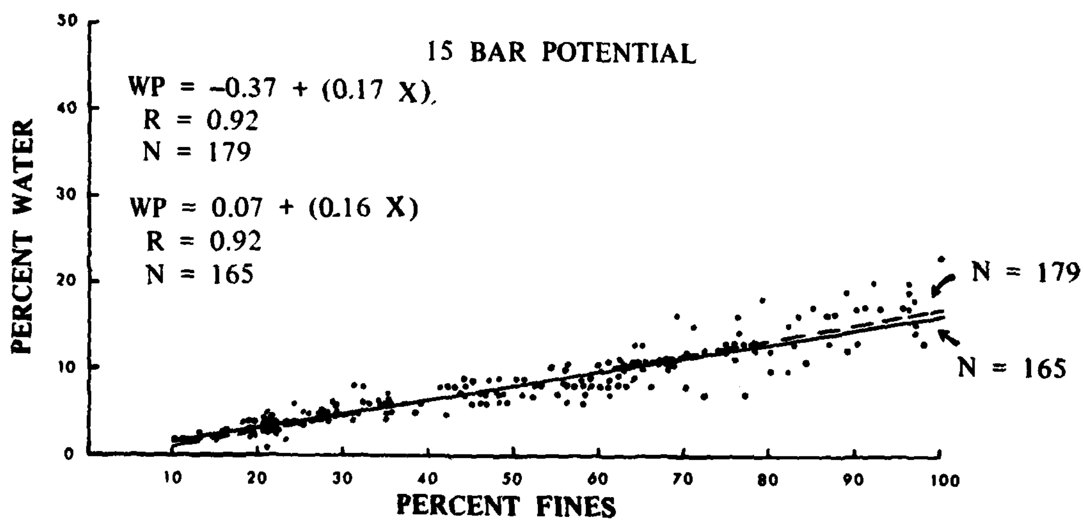


Figure 7. Percent Soil Water at 0.33 Bar and 15 Bar Potentials Plotted as a Function of Percent Fines (Silts and Clay).

curves were generated from the stepwise regression analysis of soil texture and soil water data for 179 soil samples. Regression curves were also generated from data for 165 of the 179 soil samples that did not contain weathered shale particles. Shale particles can affect soil textural and/or soil water retention parameters.

The exclusion of the data for the 14 soil samples containing the shale fragments changed the Y-intercept and the slope of the regression curves for the 0.33 and 15 bar potentials, with the more obvious changes occurring between the regression curves for the percent clay in the sample (figure 6). Strong inverse relationships were found between the percent sand and the percent soil water for the 0.33 bar and 15 bar potentials, which have correlation coefficients (multiple R values) of 0.96 and 0.93, respectively, for 179 soil samples (figure 5). The percent clay in the sample was strongly and directly correlated with the percent soil water retained at the 0.33 and 15 bar potentials, which had correlation coefficients of 0.83 and 0.90, respectively (figure 6). Samples containing more than 62 percent clay did not hold a proportionately greater amount of water. This result appears to be characteristic of a clay soil that has finite water-holding capacity.[16] The percent soil water retained by these 14 samples tended to "level off" at about 32 percent for the 0.33 bar potential and about 20 percent for the 15 bar potential.

The amount of water held was similar to amounts determined for samples containing less clay. An explanation for this situation might be related to the differences in the soil pore space for samples of different textural composition. In sandy soils, the pore space is relatively large and the forces holding the available water are relatively weak. As the pressures are applied to a saturated soil, these large pores are readily emptied of water, with only a small amount of adsorbed water on the soil particles. In clay soils, the pore sizes are smaller, more uniformly distributed, and tend to adsorb greater amounts of water. At any gradually increasing soil water potential, these soils will gradually decrease in water content.[17] The clay soils will retain more water at the higher potentials than will the sandy-textured soils at the same potential.

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[16] H. O. Buckman and N. C. Brady, *The Nature and Properties of Soils*, The MacMillan Co., New York, 1964, p. 176.

[17] Daniel Hillel, *Soil and Water, Physical Properties and Processes*, Academic Press, New York. 1971.

The 14 soil samples consisting of more than 62 percent clay also contained partially weathered shale fragments, ranging in size from fine gravel to medium sand. In the laboratory, the small size shale particles that passed through the #10 soil sieve (2.0 mm openings) remained in the sieved sample that was used for the texture and soil moisture analyses. The slaking and mechanical dispersion procedures of the hydrometer analysis resulted in complete breakup of the aggregates, including the shale particles. The breakup of the shale particles increased the amounts of clay and silt-sized particles in the sample, as suggested by Day.[18]

The procedures for making soil moisture determinations used only the sieved sample that passed the 2.00 mm sieve, but which still contained up to 90 percent sand-size shale particles of varying degrees of decomposition. These aggregates probably acted, in part, as sand-size particles in the soil moisture determinations, causing the sample to hold less water than the percentages of silt and clay would suggest. It is uncertain to what extent these aggregates affected the sample porosity. Sample number 170, which contained 64 percent clay and 36 percent silt, but no shale fragments, retained about 37 percent water at the 0.33 bar potential and 23 percent water at the 15 bar potential. Compared with the data for the 14 samples containing high clay content and shale fragments, sample number 170 held more water at both the 0.33 and 15 bar potentials. This comparison is a good indication that the soils with shale aggregates, although containing a high percentage of clay, held less water, which may have been the result of decrease soil porosity associated with the shale fragments. The effects of the shale fragments on the particle size and soil moisture relationships should be considered when determining soil moisture in soil containing weathered shale fragments.

[18]P. R. Day, "Particle fractionation and particle size analysis," *In*: C. A. Black, "Methods of Soil Analysis, Part 1, Physical and Minteralogolical Properties, Including Statistics of Measurement and Sampling," *Amer Soc of Agron*, Madison, WI, Agron Monog, Vol 9, 1965, pp. 545–577.

Stepwise multiple regression analysis showed a strong and direct relationship between the percent soil water held at the 0.33 bar (FC) and the 15 bar (WP) potentials with the percent sand plus the percent clay in the soil samples. The regression equations expressing these relationships were

$$FC = 32.9 - (0.33 \times \text{percent sand}) + (0.05 \times \text{percent clay}) \quad (2)$$
$$WP = 11.2 - (0.12 \times \text{percent sand}) + (0.09 \times \text{percent clay}) \quad (3)$$

The correlation coefficients (multiple R values) were 0.96 and 0.93, respectively.

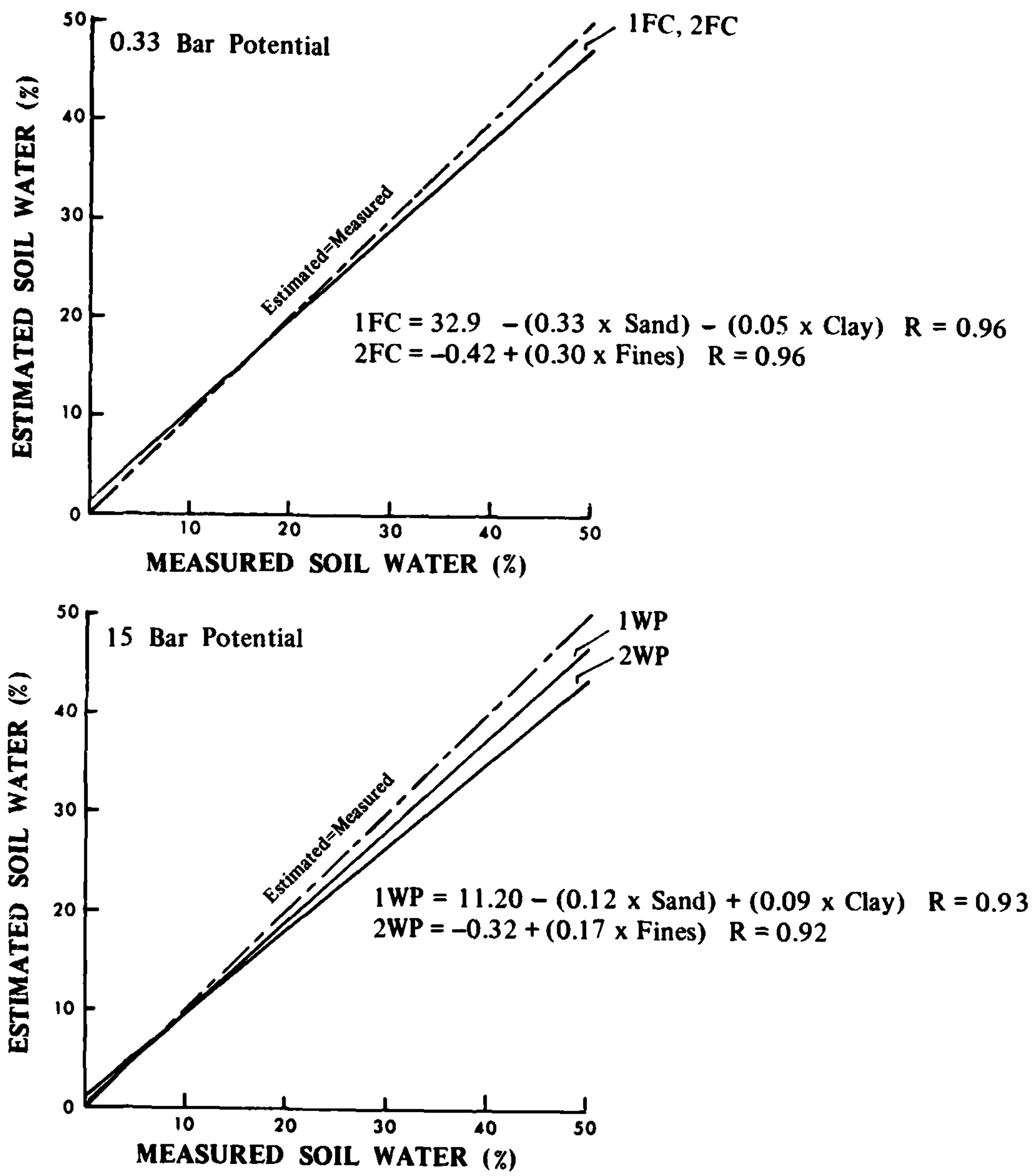
The percent water retained at the 0.33 and 15 bar potentials were also strongly and directly correlated with the percent fines (silt plus clay) in the soil sample (figure 7). Regression equations developed for these relationships were

$$FC = -0.42 + (0.30 \times \text{percent fines}) \quad (4)$$
$$WP = -0.32 + (0.17 \times \text{percent fines}) \quad (5)$$

The correlation coefficients (multiple R values) were 0.96 and 0.92, respectively.

Estimates of the percent water retained at FC and WP were calculated using the soil textural data, and regression equations 2, 3, 4, and 5. The range and the mean soil water percentage were estimated by using the same equations (table 1). The extimated soil water values were compared with the measured soil water values using the Chi-square, which showed that the differences observed between the estimated and measured values were not significant at the 95 percent confidence level.

The regression curves of the estimated percent soil water determined from equations 2 and 4 are compared with the measured percent soil water retained at the 0.33 bar potential (figure 8). The regression curves show that equations 2 and 4 had essentially the same plot and that there was little difference between their capability to predict soil water, given the necessary textural data.



Note: Estimates were made using, (1) Percent Sand and Percent Clay, and (2) Percent Fines in the less than 2.0 mm Soil Fraction. (N–179).

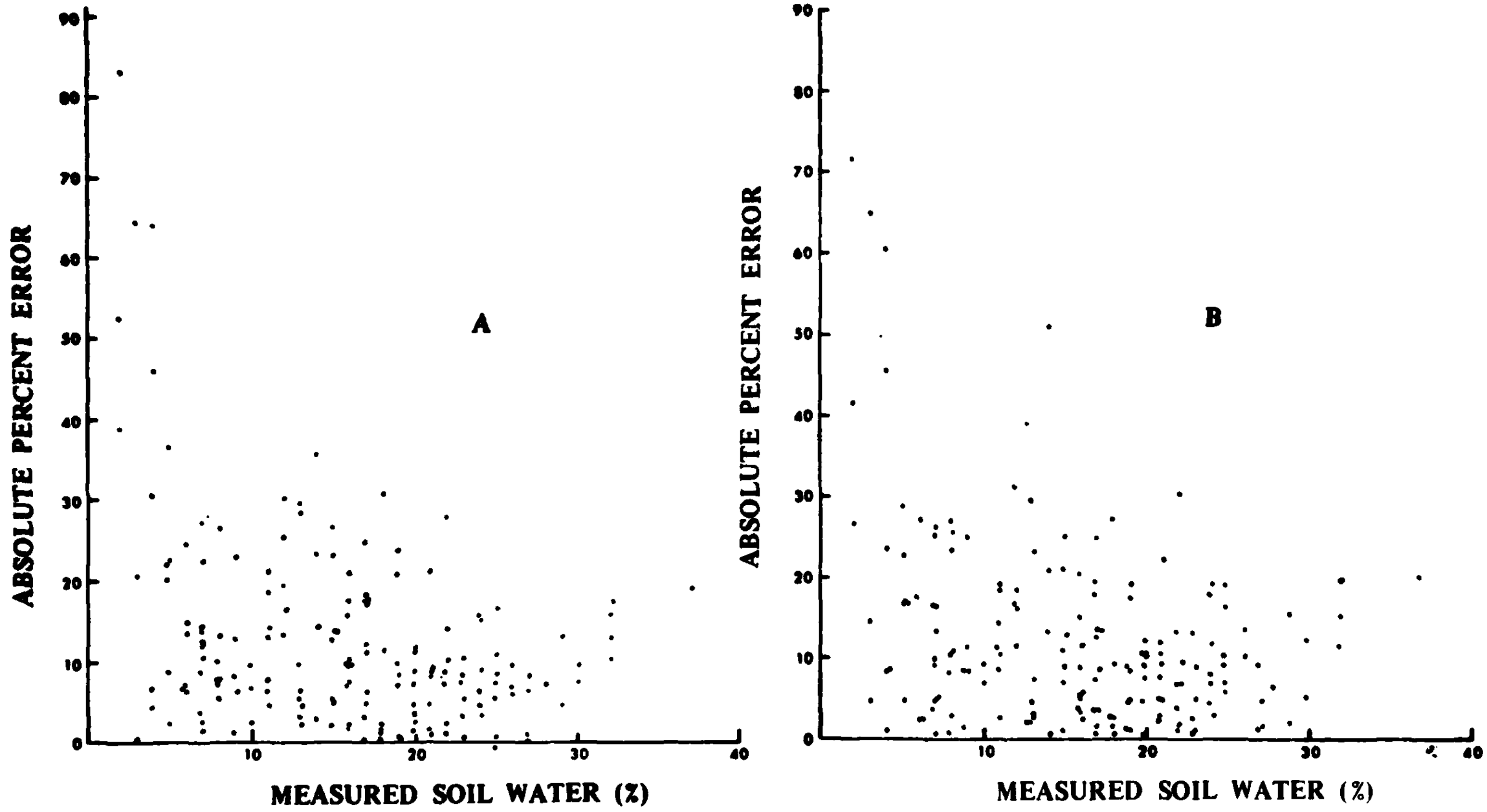
Figure 8. Regression Curves Comparing Measured and Estimated Percent Soil Water for the 0.33 Bar and 15 Bar Potentials.

The regression curves in figure 8 show that equations 2 and 4 generally overestimated the water retention for soils retaining less than approximately 15 percent water at the 0.33 bar potential. These estimates and the data presented in figures 5, 6, and 7 indicate a slight overestimation of the percent soil water at the 0.33 bar potential should be anticipated for soils containing >50 percent sand, <32 percent clay, or <52 percent fines, and at the 15 bar potential for soils containing >39 percent sand, <39 percent clay, or <61 percent fines.

Conversely, an underestimation of the soil water retained should be anticipated at the 0.33 bar potential for those soils containing <50 percent sand and >32 percent clay, or >52 percent fines; and at the 15 bar potential for soils containing <39 percent sand, >39 percent clay, or >61 percent fines.

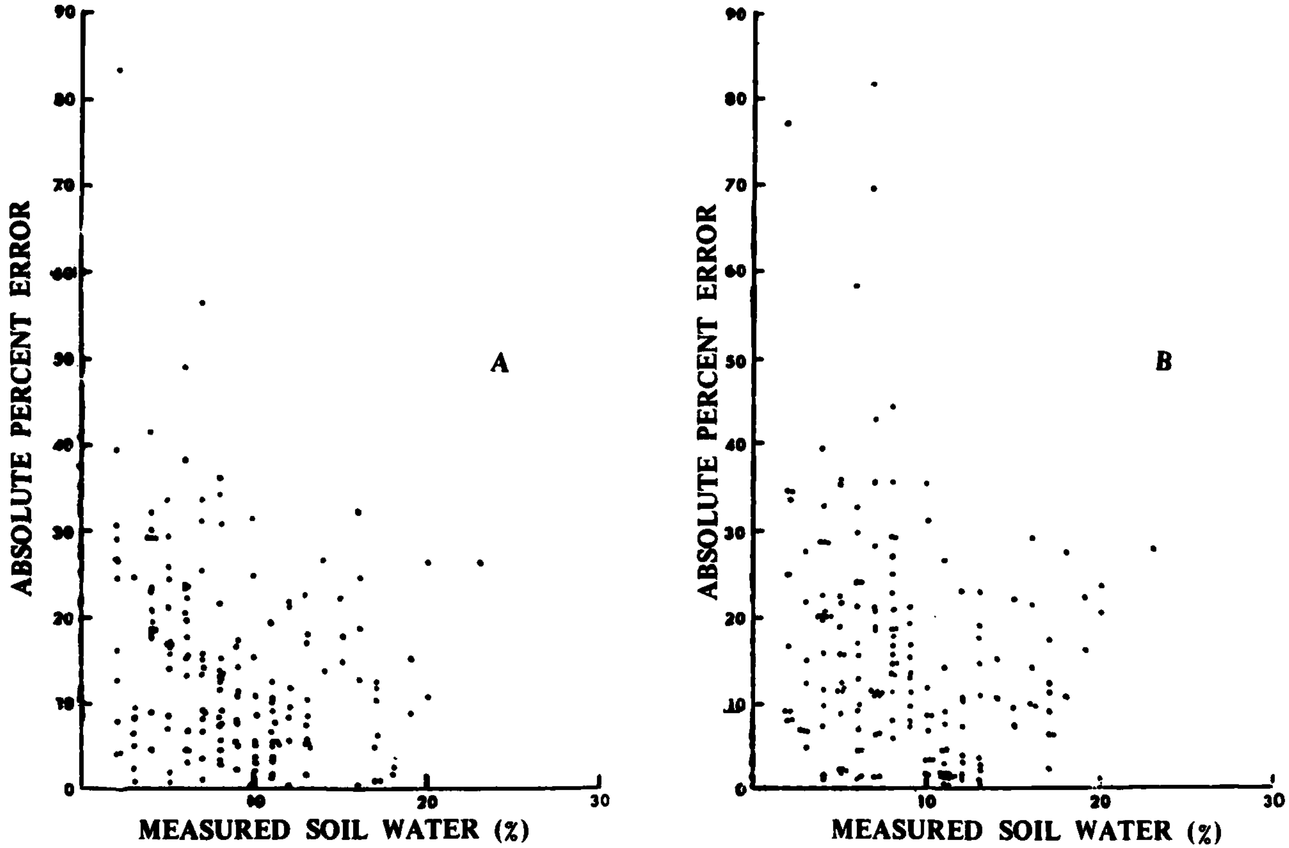
The absolute percent error calculated between the measured and the estimated percent soil water at FC (equations 2 and 4) are shown in figure 9. Of the estimated values, 94 percent had absolute percent errors less than 30 percent of measured values. These were soils consisting of >83 percent sand and $\leqslant 13$ percent clay. The FC estimates with >30 percent absolute error were made for primarily sands, loamy sands, or sandy loams soils.

Estimates of percent soil water retention at the WP (equations 3 and 5) were compared with the measured percent soil water (figure 8). The differences between the estimated WP and the measured WP values were slightly greater for the estimates made from equation 5; however, this difference was not a significant one. The absolute percent error between the measured and the estimated WP values are shown in figure 10 for equations 3 and 5. Most (90 percent) of the estimates had absolute percent errors less than 20 percent. Estimates having >20 percent error were generally associated with soils retaining less than about 10 percent soil water at the 15 bar potential, which were soils consisting of >69 percent sand and <39 percent clay (figure 5 and 6). The textural classes of these soils were sands, loamy sands, and loams.



Note: Estimates were made using (A) Percent Sand and Percent Clay and (B) Percent Fines in the less than 2.0 mm Sample Fraction. (N = 179)

Figure 9. Absolute Percent Error Between Estimated and Measured Percent Soil Water at 0.33 Bar Potential.



Note: Estimates were made using (A) Percent Sand and Percent Clay and (B) Percent Fines in the less than 2.0 mm Sample Fraction. (N = 179)

Figure 10. Absolute Percent Error Between Estimated and Measured Percent Soil Water at the 15 Bar Potential.

Although differences were observed in the relationships between the percent clay and percent water retained in the soil (figure 6) for those soils containing >62 percent clay, these differences were not found in the various estimates of percent water and the percent error associated with these estimates. Unlike the data presented in figure 6, where a discrete cluster of samples identifiable as those samples containing a substantial percentage of sand size shale fragments/particles, the data presented in figures 9 and 10 did not show a clustering of these particular samples. The percent soil water estimated for these 14 samples had percent errors less than 30 percent which were comparable to the range of percent error associated with soils not containing shale particles. This suggests that the shale particles had a smaller impact on the texture-soil water relation than was previously believed.

Although the regression equations provided good estimates of the FC and WP, the predictive use of such equations in other similar geographic areas will require further evaluation. However, the confidence level associated with using these or similar regression equations for predicting FC and WP can be assessed somewhat by using the regression equations developed by Schmugg[19] et al. for the soils near Phoenix, Arizona (equations 6 and 7).

$$\mathrm{FC} = 25.1 - (0.21 \times \text{percent sand}) + (0.22 \times \text{percent clay}) \quad (6)$$

$$\mathrm{WP} = 7.2 - (0.07 \times \text{percent sand}) + (0.24 \times \text{percent clay}) \quad (7)$$

Using equations 6 and 7, one can estimate the soil water retained at the FC and WP from the soil textural data generated in this study, a test that indicates the applicability of using regression equations developed for the soils of one area for estimating FC and WP values in other regions. The estimated FC values ranged from 8.2 to 44.5 percent, with a mean of 22.5 percent; and the estimated WP values ranged from 3.1 to 28.3 percent, with a mean of 11.9 percent. Compared with the measured values summarized in Table 1,

[19] T. Schmugge, T. Wilheit, W. Wester, and J. Gloersen, *Remote Sensing of Soil Moisture With Microwave Radiometers--II.* NASA TN D8321, N76-32625, 1976.

equations 6 and 7 generally overestimated the percent soil water retained by the soils in this study. The difference was significant at the 95 percent level of confidence and 178 degrees of freedom. Figure 11 compares the regression curves for the estimated soil water at FC and WP, using the regression equations developed here and using equations 6 and 7, as reported by Schmugge.[20] Equations 6 and 7 overestimated the percent soil water at FC and WP for most soil samples.

Apparently, the use of regression equations developed for the soils of one area and used in another area for predicting FC and WP may have limited use. From a practical point of view and when precise values are not needed, these equations can provide useable working estimates of the soil water retention at FC and WP. The level of precision in estimating FC and WP using regression equations was in agreement with that reported by Schmugge.[21] The estimated percent soil water at FC, using equations 2 and 4, varied ±25 percent of the measured soil water for about 93 percent of the samples. Using equations 3 and 5, estimates varied ±30 percent of the measured WP values for about 90 percent of the samples. The estimated percent soil water for FC and WP calculated from equations 6 and 7 had percent error values that were ±50 percent of the measured soil water.

[20] T. Schmugge, T. Wilheit, W. Wester, and J. Gloersen, *Remote Sensing of Soil Moisture With Microwave Radiometers--II.* NASA TN D8321, N76-32625, 1976.

[21] Ibid.

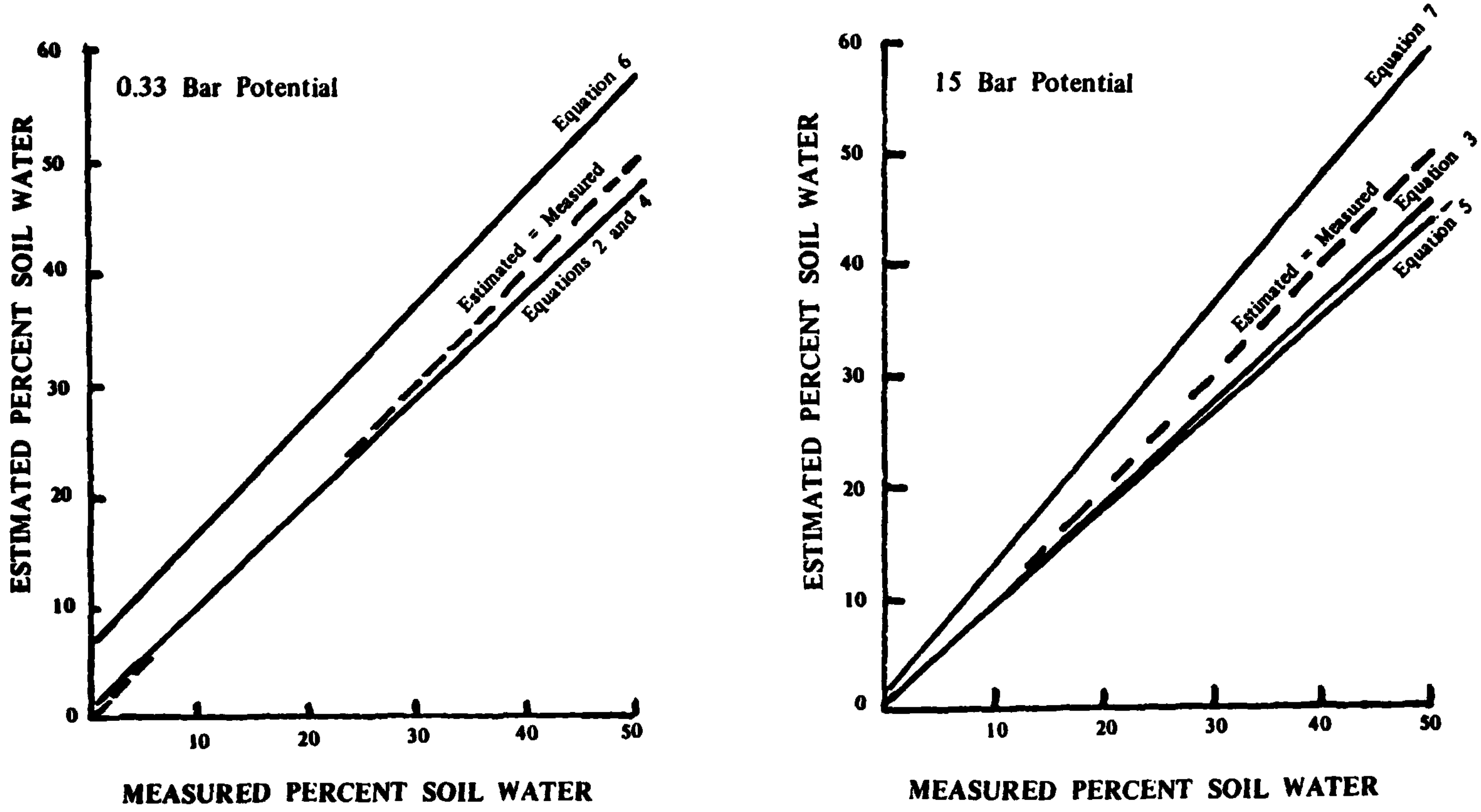


Figure 11. Comparison of Estimated FC and WP Values Using Three Regression Equations With the Measured FC and WP.

CONCLUSIONS

Conclusions are presented in the order of the experimental results. The amount of water held in a soil was inversely related to the percent sand, and directly related to the percent clay or to the percent fines in the soil. Furthermore, the percent sand plus the percent clay were highly correlated with the percent soil water retained in the soil at the 0.33 and 0.15 bar potentials.

> **Note**: These dependencies, which are known to soil scientists and which are verified by these experiments, are important because they suggest the possibility of establishing a mathematical relationship such that useful predictions about soil moisture could be made from a knowledge of soil texture and local meteorological conditions. Indeed, such a relation was established.

Regression equations were developed from these soil texture-soil moisture relationships. If one uses the percentages of sand and clay, or the percent fines in the soil, statistically valid estimates at the 95 percent level of confidence of the percent soil water reatined at the 0.33 and 15 bar potentials can be obtained.

$$FC = 32.9 - (0.33 \times \text{percent sand}) + (0.05 \times \text{percent clay})$$
$$FC = -0.42 + (0.30 \times \text{percent fines})$$
$$WP = 11.2 - (0.12 \times \text{percent sand}) + (0.09 \times \text{percent clay})$$
$$WP = -0.32 + (0.17 \times \text{percent fines})$$

Although these relationships that were established are valid, there is a disparity between the methods of handling the soil samples for soil texture measurements as compared to soil moisture measurements. This disparity can greatly influence the results. During the soil textural analysis, soil aggregates or weathered rock fragments that pass the 2 mm sieve are broken into smaller sized particles. In the soil moisture analysis these aggregates are not broken into smaller particles and can retain their integrity and function as large sized particles. Such a sample would hold less soil water than a sample composed of individual small sized particles. The result could be an erroneous soil textural-soil moisture relationship that would reduce the predictive capability of equations developed from this relationship.

Regression equations can be used for making acceptable working estimates of the FC and WP for the soils in other areas; however, these estimates can be significantly different from measured values.

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